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Effects of limited previously acquired information about falling height on lower limb biomechanics when individuals are landing with limited visual input

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ABSTRACT

Background: Inhibitions in the acquisition of accurate information about the environment can affect control of the lower extremities and lead to anterior cruciate ligament injury. This study aimed to clarify the effects of limited prior knowledge of the height of the fall, as well as limited visual input, on lower limb and trunk motion and ground reaction force during landing.

Methods: Twenty healthy university students were recruited. Drop landings from a 30-cm platform were measured under three conditions: (1) unknown, without prior knowledge of the height of the fall and without visual input; (2) known, with prior knowledge of the height of the fall and without visual input; and (3) control, with prior knowledge of the height of the fall and visual input.

Findings: In the unknown condition, the peak ground reaction force for the vertical and posterior directions was significantly higher than that in the known and control conditions; leg and knee stiffness, ankle joint work, and joint flexion motion of the knee, ankle, and trunk after landing were decreased as well. In the known condition, there were no significant differences in leg and knee stiffness and vertical ground reaction force compared to the control condition.

Interpretation: The results of this study indicate that the risk of anterior cruciate ligament injury during landing increases when individuals have limited visual input and prior knowledge of the height of the fall. This finding suggests that an accurate perception of the surrounding environment may help prevent anterior cruciate ligament injuries.

1. Introduction

Anterior cruciate ligament (ACL) injury is one of the most common injuries sustained during sports activities (Alentorn-Geli et al., 2009; Krosshaug et al., 2007; Mullally et al., 2021). Prevention of ACL injuries is essential and beneficial for a variety of athletes, considering that it takes 6–9 months to return to sports after undergoing an ACL reconstruction (Harris et al., 2014; Kaplan and Witvrouw, 2019). Even if these individuals resume playing sports, several exhibit reduced performance and experience shortened athletic careers (Niederer et al., 2018). In addition, people with ACL injuries are at a high risk of re-injury (Kim et al., 2017). Therefore, prevention of ACL injury is important for individuals involved in sports.

Postural control is one of the factors associated with ACL injuries. Most ACL injuries that occur when individuals participate in sports activities are non-contact injuries (Koga et al., 2010; Sandon et al., 2021). Kinematic and kinetic factors, such as increased knee joint valgus and ground reaction forces (GRFs), are associated with ACL injuries (Koga et al., 2010). In the case of non-contact ACL injuries, neuromuscular activity plays a significant role in regulating the kinematics and kinetic factors of the lower limb joints.

For proper postural control, it is crucial to obtain accurate information about the environment. Visual input plays a significant role in perceiving the surrounding environment and obtaining appropriate postural control (Choy et al., 2003; Hsu et al., 2007; Schwesig et al., 2011; Shafer et al., 2019). Patients with ACL injuries or those who have

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undergone reconstructive surgery have reduced knee proprioceptive function (Kim et al., 2017). Therefore, compensation with visual information is effective in acquiring normal knee joint motion (Louw et al., 2015; Monfort et al., 2019). However, visual input is likely to be inhibited during sports activities because other players may obstruct the view of individuals and concentration on external objects is required. Indeed, many ACL injuries occur when a player is followed by an opponent or is focused on external objects such as the basket rims and the ball (Krosshaug et al., 2007). Visual disturbances have little effect on motor control of the lower limbs if the surrounding environment is known (Liebermann and Goodman, 2007). This result emphasizes the importance of considering prior knowledge of the environment. Thus, to examine the factors contributing to ACL injuries, it is crucial to clarify the influence of prior knowledge of the surrounding environment on lower limb kinematics and kinetics in the presence of limited visual input.

The height of the fall is one of the most critical factors affecting postural control when an individual is landing. Improper landing movement is one of the most common causes of ACL injuries (Alentorn-Geli et al., 2009; Mullally et al., 2021). The height of the fall is a significant factor that determines the amount and timing of GRFs. Previous studies have reported that limited prior information about drop height reduces the GRF and limb joint movement during drop jumps, resulting in poor jump performance after landing (Helm et al., 2019; Helm et al., 2020). These studies measured the kinematic characteristics of lower limb joints, but comprehensive body movements, including trunk movements, have not been examined. Trunk motion influences vertical and posterior GRFs during landing (Alentorn-Geli et al., 2009; Ali et al., 2014); these increases are risk factors for ACL injuries (Leppänen et al., 2017; Sell et al., 2007) and should be assessed for injury prevention.

Therefore, the purpose of this study was to investigate the effects of prior knowledge of the height of fall on the kinematics and kinetics of the lower limbs and trunk and the GRF applied to the body during landing movements in a visually restricted environment. The hypothesis was that limited visual input combined with limited prior knowledge of the height of fall would result in lower performance of landing movements and motions with a high risk of ACL injuries (e.g., large GRF and reduced joint motion).

2. Methods

2.1. Participants

Twenty healthy university students (10 males and 10 females), aged 21.5 ± 2.1 years (mean $\pm$ SD) were recruited as participants. The participants had no medical history of orthopaedic disease of the lower extremities or trunk. Before testing, the participants were informed of the experimental procedures, which were approved by the Institutional Review Board (Hiroshima University, Hiroshima, Japan) (approval number: E-1158). After confirming that they understood the procedures, the participants provided written informed consent.

2.2. Procedure

Drop landing from a 30-cm platform was adopted as the measurement task. Two types of falling heights (30 and 20 cm) were used in this study. A 10-cm platform was installed at the landing point if the falling height was changed to 20-cm.

Before the measurements were taken, the participants performed practice trials. Participants received the following three instructions: (1) to land on both feet, (2) to land softly, and (3) not to move for a particular duration of time after landing. The preliminary trials were performed a total of eight times. In the first four trials, the participants performed drop landing twice at each of the two falling heights, with their eyes open. Subsequently, the participants performed the same exercise with their vision obstructed by a band around their eyes.

Following the practice trials, the landing behaviors of the participants were measured. There was a 5-min break after the practice trials to reduce the effects of fatigue. The participants were instructed to start the movement voluntarily after receiving the cues to start the measurement. A successful trial was defined as one in which the participant performed a stable landing on both legs. The trials were treated as failures if the following behaviors occurred: taking a step after landing or landing with one foot on the ground first. Additionally, the data measured when individuals landed from a height of 30 cm were treated as the representative values.

2.3. Measurement conditions

Three conditions were chosen to investigate the effect of prior knowledge about falling height on landing biomechanics (unknown: without prior knowledge of the height of fall and without visual input; known: with prior knowledge of the height of fall but without visual input; and control: with prior knowledge of the height of fall and visual input). The same participants performed the drop landing task under all conditions in the following order: unknown, known, and control. The details of each condition are described below.

The unknown condition was used to obtain biomechanical data without the participants having prior knowledge of the falling height. In this condition, a blindfold was placed on the participants to control the situation so that they could not see the height of the fall. The participants were informed that the falling height was decided at random and that they could not know the height of the fall in advance. In this state, the participants were instructed to perform the drop-landing task.

Data collected in the known condition were set as control data to be used when evaluating the effect of prior knowledge of the falling height on landing biomechanics. Under this condition, the participants were also instructed to perform the trial while wearing a blindfold. Unlike in the unknown condition, the falling height was fixed at 30 cm, and participants were informed of the falling height before the trial.

Data collected in the control condition were used as control data to be used when examining the effect of visual information on landing biomechanics. Unlike in the other two conditions, the participants were instructed to perform the trial without wearing a blindfold. Additionally, the falling height was fixed at 30 cm, and the participants could visually detect the falling height.

Moreover, in the unknown condition, the value measured in the first trial was treated as a representative measurement that could be used to obtain data unaffected by habituation to the condition. In the known and control conditions, measurements were performed until three successful trials were measured, and the mean values for the three trials were treated as representative.

2.4. Equipment

A three-dimensional motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK) with 16 infrared cameras and two force plates (AMTI, MA, USA) was used to obtain the kinematics and kinetics of the trunk and lower limbs. The sampling frequencies of the kinematics and kinetics were 100 Hz and 1000 Hz, respectively.

The trajectories of infrared reflective markers were measured. The markers were placed on the body, referring to the point cluster technique (Andriacchi et al., 1998) to calculate the knee kinematics. Additional markers were placed on the acromion, anterior superior iliac spine, posterior superior iliac spine, medial malleolus, head of the fifth metatarsal bone, and lateral side of the calcaneus; these markers were used to calculate the kinetics and kinematics of the trunk, hip, and ankle.

The GRF was measured using two force plates placed adjacent to each other on the left and right sides.

2.5. Data processing

The Vicon Nexus (Vicon Motion Systems, Oxford, UK) was used to calculate the participants' kinematics and kinetics. We defined five segments: the trunk, pelvis, thigh, shank, and foot. The body center of mass (CoM) was calculated from the position data of each segment.

We calculated participants' knee kinematics using the point cluster technique (Andriacchi et al., 1998). The local coordinate system for each segment was defined as the medial and lateral directions with the x-axis positive to the right, the anterior and posterior directions with the y-axis positive to the anterior, and the vertical direction with the z-axis positive upward. The rotational motion of the joint was represented by a z-x-y rotation sequence. The hip, ankle, and trunk flexion angles were calculated as the rotation of the thigh, foot, and trunk segments relative to the pelvis, shank, and pelvis segments around the x-axis, respectively. The GRF data were low-pass filtered (Butterworth 4th-order filter, cutoff frequency 6 Hz). Data regarding the knee, hip, and ankle joint moments and power were calculated using inverse dynamics.

The representative values were defined as follows:

For the GRF data, the maximum values in the vertical and posterior directions were calculated as peak vGRF and pGRF, respectively. Additionally, the time from foot contact to the peak vGRF and pGRF was calculated. The landing phase was defined as the time from initial contact to the peak vGRF. For the CoM data, the changes in the vertical and anterior directions of the CoM during the landing phase were calculated as vCoM and aCoM, respectively.

In the kinematic data analysis, the joint angles at the time of foot contact and the peak vGRF were extracted as the representative values. Additionally, the excursion between the aforementioned values was calculated. In the kinetic data analysis, the joint moment data at the time of the peak vGRF occurrence were extracted as the representative values.

The joint work, leg stiffness, and joint stiffness were calculated for the performance data. Joint work was calculated as the integral of joint power values in the landing phase at the knee, hip, and ankle joints. Body and joint stiffness were calculated to assess the kinematic properties of the entire lower extremity and each joint in response to the GRF. Leg stiffness was calculated by dividing the peak vGRF by the vCoM shift. Joint stiffness was calculated by dividing the internal extension (plantar flexion) moment at the time of the peak vGRF by the respective joint angle excursions at the knee, hip, and ankle joints.

2.6. Statistics

One-way repeated-measures analysis of variance and post hoc test using Shaffer's procedures were performed to examine the effects of the conditions on the representative values. Mauchly's sphericity test was used to examine within-subject equivariance. When the equivariance hypothesis was rejected, the Greenhouse-Geisser method was used to correct for degrees of freedom. Statistical significance was set at $p < .05$.

3. Results

3.1. GRF, CoM, and motor performance

The GRF results are shown in Fig. 1 and the CoM shift and stiffness results are listed in Table 1.

The peak vGRF and pGRF were significantly higher in the unknown condition than in the other two conditions ($p < .01$). The peak pGRF was significantly higher in the known condition than in the control condition ($p < .01$). There was no significant difference among the three groups regarding the time of appearance of the peak vGRF and pGRF.

The vCoM shift showed a significant main effect of condition in ANoVA ($p = .031$), but there was no significant difference among the groups in post hoc tests. In the unknown condition, the pCoM shift was significantly smaller than that in the other two conditions ($p < .01$), and the shift in the known condition was significantly smaller than that in the control condition ($p < .01$).

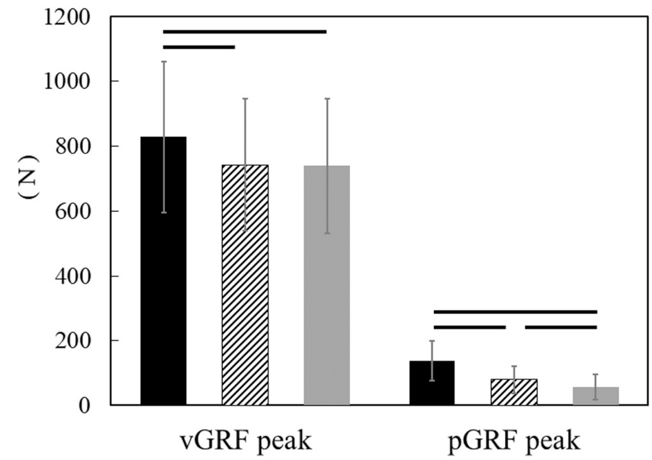

Fig. 1. Peak values of vGRF and pGRF.
The bars indicate significant changes among groups ($p < .05$). The black filled shapes, shaded line, and grey filled shapes represent unknown, known, and control condition data, respectively.

Leg stiffness and knee joint stiffness were significantly higher in the unknown condition than in the other two conditions ($p < .01$).

Ankle joint work was significantly lower in the control, known, and unknown conditions, in that order. Hip joint work was significantly lower in the unknown condition than in the control condition ($p < .01$).

3.2. Joint kinematics and kinetics

The time-series changes in joint angles and their respective representative values are shown in Fig. 2 and Table 2.

3.2.1. Initial contact

The knee flexion angle was significantly greater and the ankle plantar flexion angle was significantly smaller in the unknown condition than in the other two conditions ($p < .01$). No significant differences were observed between the known and control conditions.

3.2.2. At GRF peak

The trunk flexion angle was significantly smaller in the unknown condition than in the other two conditions ($p < .01$); there was no significant difference between the known and control conditions.

The representative values of the joint moments are listed in Table 2. There were no significant differences in joint moments among the three groups.

3.2.3. Excursion

In the unknown condition, the changes in trunk, knee, and ankle joint flexion (dorsiflexion) were significantly smaller than those in the other two conditions ($p < .01$). The hip flexion angle excursion was significantly smaller in the unknown condition than in the control condition ($p < .01$), but there was no significant difference between the unknown and known conditions. In the known condition, the changes in the trunk and hip flexion angles were significantly smaller than those in the control condition ($p < .01$).

4. Discussion

The most important finding of this study was that limited prior knowledge of the height of fall caused an increase in vGRF and pGRF and a decrease in post-landing knee flexion excursion when individuals landed under conditions of limited visual input. These factors increase the risk of ACL injuries (Leppänen et al., 2017; Sell et al., 2007).

Table 1
Representative values of GRF, CoM, and motor performance.

	Mean (95% CI)			ANoVA		Post hoc					
	Unknown	Known	Control	Main effects of conditions (p -value)	partial η^2	Effect size *d* (unknown - known)	Effect size *d* (unknown - control)	Effect size *d* (known - control)	p -value (unknown - known)	p -value (unknown - control)	p -value (known - control)
vGRF peak (N)	828.1 (716.6–939.7)	741.8 (644.1–839.4)	740.0 (640.2–839.8)	**0.001**	0.362	0.378	0.382	0.008	**0.005**	**0.001**	0.918
pGRF peak (N)	137.8 (107.8–167.8)	79.7 (59.9–99.5)	57.1 (38.0–76.3)	**0.000**	0.583	1.049	1.472	0.531	**0.000**	**0.000**	**0.010**
vGRF peak timing (ms)	61 (54.6–67.4)	68 (58.6–77.4)	69.8 (62.0–77.7)	0.093	0.122	−0.398	−0.564	−0.097	0.157	0.068	0.631
pGRF peak timing (ms)	94 (73.8–114.2)	91.2 (72.1–110.2)	85.8 (65.7–105.9)	0.427	0.039	0.066	0.186	0.125	0.715	0.319	0.482
vCoM shift (mm)	112.7 (103.5–121.9)	127.2 (117.1–137.2)	129.8 (119.2–140.4)	**0.031**	0.197	−0.688	−0.790	−0.118	0.139	0.086	0.428
pCoM shift (mm)	23.1 (19.7–26.5)	30.1 (26.5–33.8)	34 (31.0–37.0)	**0.000**	0.550	−0.915	−1.558	−0.535	**0.002**	**0.000**	**0.003**
Leg stiffness (N /m)	7.6 (6.4–8.7)	6.1 (5.1–7.1)	6.1 (4.8–7.3)	**0.001**	0.349	0.632	0.586	0.013	**0.003**	**0.007**	0.898
Joint stiffness											
Knee (Nm /degree)	3.7 (2.9–4.6)	3 (2.4–3.5)	2.7 (2.1–3.4)	**0.000**	0.352	0.486	0.610	0.189	**0.004**	**0.002**	0.237
Hip (Nm/ degree)	1.7 (0.8–2.5)	1.4 (0.8–2.1)	1.4 (0.8–2.0)	0.554	0.025	0.157	0.201	0.048	0.536	0.403	0.765
Ankle (Nm /degree)	0.4 (0.2–0.6)	0.5 (0.4–0.7)	0.5 (0.3–0.7)	0.259	0.068	−0.351	−0.279	0.028	0.455	0.282	0.842
Joint work											
Knee (J)	−1.9 (−2.3 - -1.6)	−2 (−2.3 - -1.7)	−2 (−2.4 - -1.7)	0.582	0.024	0.136	0.159	0.024	0.450	0.477	0.866
Hip (J)	−0.1 (−0.2–0.0)	−0.3 (−0.3 - -0.2)	−0.4 (−0.5 - -0.2)	**0.011**	0.233	0.558	0.873	0.429	0.084	**0.032**	0.055
Ankle (J)	−1.4 (−1.7 - -1.1)	−1.8 (−2.2 - -1.4)	−2 (−2.4 - -1.6)	**0.004**	0.347	0.501	0.742	0.220	**0.013**	**0.003**	**0.004**

Bold text indicates $p < .05$. CI: confidence interval, ANoVA: analysis of variance, GRF: ground reaction force, CoM: centre of mass.

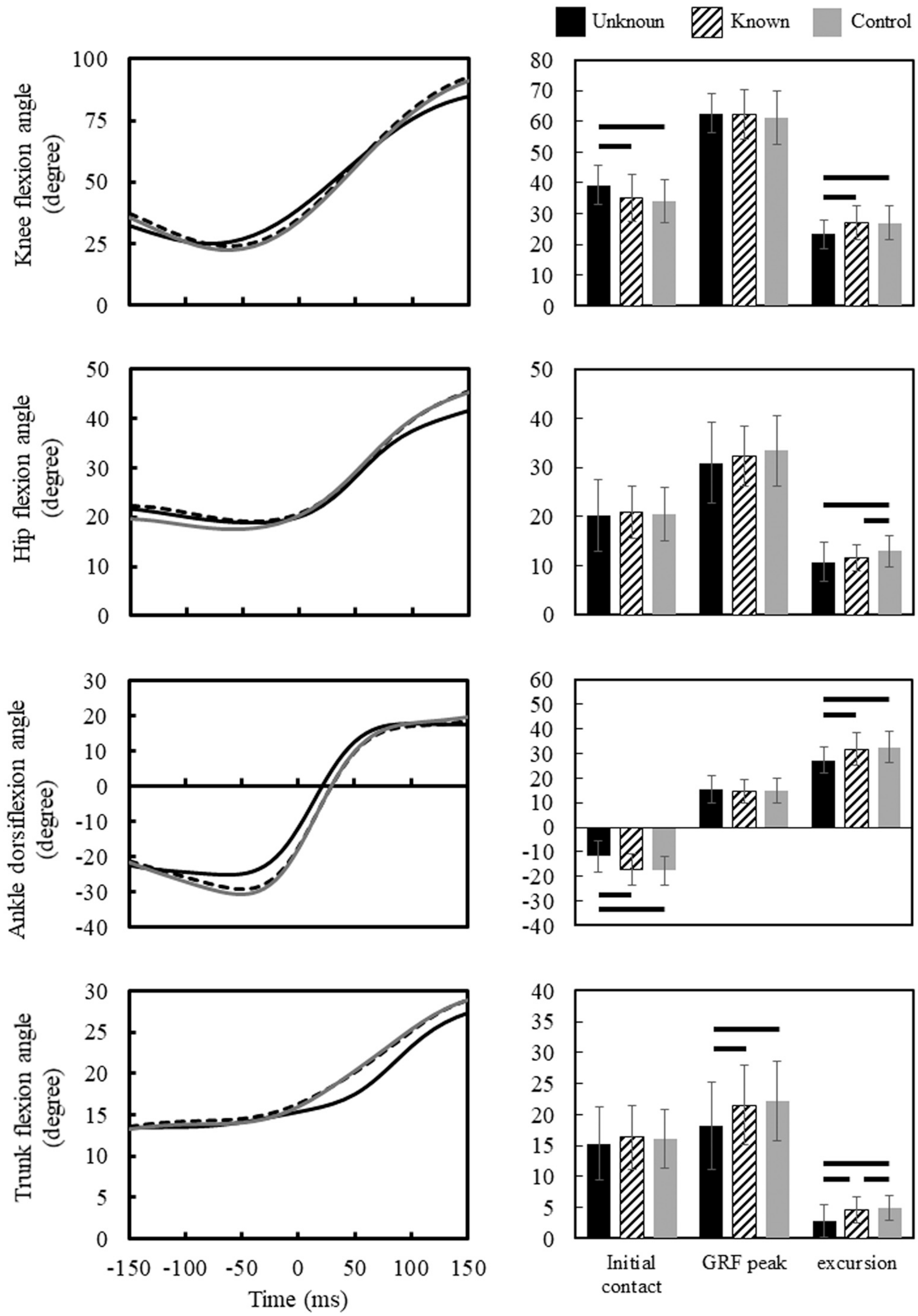

Fig. 2. Temporal changes in joint angle during landing (left column) and representative values (right column). The bars indicate significant changes among groups ($p < .05$). The point of initial contact is described as time zero. The solid line and black filled shapes represent the unknown condition data. The dotted line and the shaded line represent the data of the known condition. Grey lines and grey filled shapes represent the data of the control condition. GRF: ground reaction force.

This study showed that a lack of prior knowledge of the height of fall significantly increased the vGRF in a visually restricted environment. This result is inconsistent with that of a previous study (Helm et al., 2020). The reason for this inconsistency lies in the different objectives of task operations. In the previous study, the drop-jump motion was used as the task motion, and an increase in GRF was reasonable with higher jumps. In the present study, the landing motion was used as the task motion, and the participants were required to absorb the impact of landing; therefore, the observed suppression of the GRF was reasonable. From the above, it is conceivable that rational behavior is suppressed in the non-prediction condition. When prior knowledge of the height of the fall was available, there were no significant changes in vGRF. Furthermore, it has been reported that there is no change in the GRF during landing movements with restricted visual input compared to unrestricted visual input (Liebermann and Goodman, 2007). The results of the present study support the findings of this previous study. An increased vGRF is associated with the occurrence of various knee joint injuries, including ACL injuries (Leppänen et al., 2017). Therefore, the results of this study suggest that limited prior knowledge of fall height increases the risk of knee joint injuries. There are two possible

Table 2
Representative values of joint kinematics and kinetics.

	Mean (95% CI)			ANoVA		Post hoc					
	Unknown	Known	Control	Main effects of conditions (p -value)	partial η^2	Effect size *d* (unknown - known)	Effect size *d* (unknown - control)	Effect size *d* (known - control)	p -value (unknown - known)	p -value (unknown - control)	p -value (known - control)
Initial contact											
Knee flexion angle (degree)	39.2 (36.2–42.3)	35.3 (31.6–38.9)	34.3 (30.9–37.6)	**0.002**	0.353	0.537	0.707	0.133	**0.011**	**0.003**	0.124
Hip flexion angle (degree)	20.2 (16.7–23.7)	20.8 (18.2–23.3)	20.5 (17.8–23.1)	0.783	0.012	−0.087	−0.040	0.056	0.537	0.779	0.672
Ankle flexion angle (degree)	−11.8 (−14.9 - -8.7)	−17.2 (−20.2 - -14.2)	−17.7 (−20.5 - -14.9)	**0.002**	0.383	0.820	0.928	0.082	**0.004**	**0.003**	0.371
Trunk flexion angle (degree)	15.3 (12.5–18.2)	16.3 (13.8–18.8)	16.1 (13.8–18.3)	0.228	0.075	−0.171	−0.131	0.050	0.235	0.307	0.610
At GRF peak											
Knee flexion angle (degree)	62.6 (59.5–65.7)	62.2 (58.4–66.0)	61.3 (57.1–65.4)	0.469	0.036	0.048	0.166	0.111	0.792	0.301	0.719
Hip flexion angle (degree)	30.9 (27.0–34.9)	32.3 (29.4–35.3)	33.4 (30.0–36.8)	**0.033**	0.167	−0.188	−0.307	−0.149	0.144	0.052	0.211
Ankle flexion angle (degree)	15.4 (12.8–18.0)	14.4 (12.1–16.8)	14.9 (12.5–17.3)	0.323	0.056	0.185	0.099	−0.087	0.533	0.493	0.334
Trunk flexion angle (degree)	18.3 (14.9–21.7)	21.5 (18.5–24.6)	22.1 (19.0–25.2)	**0.000**	0.515	−0.465	−0.543	−0.083	**0.000**	**0.000**	0.295
Excursion											
Knee flexion angle (degree)	23.4 (21.1–25.6)	26.9 (24.3–29.6)	27.0 (24.4–29.6)	**0.000**	0.431	−0.679	−0.698	−0.012	**0.001**	**0.000**	0.921
Hip flexion angle (degree)	10.7 (8.8–12.6)	11.6 (10.3–12.9)	12.9 (11.4–14.4)	**0.003**	0.284	−0.239	−0.583	−0.436	0.124	**0.012**	**0.013**
Ankle flexion angle (degree)	27.2 (24.7–29.8)	31.7 (28.5–34.8)	32.6 (29.6–35.7)	**0.006**	0.287	−0.710	−0.879	−0.143	**0.019**	**0.013**	0.269
Trunk flexion angle (degree)	2.9 (4.2–1.6)	4.6 (5.7–3.6)	5.2 (6.1–4.2)	**0.000**	0.514	−0.679	−0.900	−0.240	**0.000**	**0.000**	**0.024**
Joint moment at vGRF peak											
Knee extension moment (Nm)	82.8 (66.5–99.1)	74.5 (63.7–85.4)	74.8 (64.1–85.4)	0.051	0.172	0.274	0.267	−0.010	0.138	0.061	0.887
Hip extension moment (Nm)	15.4 (9.1–21.7)	16 (9.9–22.0)	17.4 (10.9–23.9)	0.772	0.011	−0.044	−0.140	−0.100	0.874	0.528	0.585
Ankle planter flexion moment (Nm)	−10.9 (−15.6 - -6.3)	−14.8 (−18.3 - -11.4)	−14.8 (−19.6 - -10)	0.120	0.113	0.435	0.373	−0.006	0.205	0.142	0.970

Bold text indicates $p < .05$. CI: confidence interval, ANoVA: analysis of variance, GRF: ground reaction force.

explanations for the increase in vertical GRF: an increase in leg stiffness and a decrease in ankle joint work.

Increase in vGRF is influenced by increase in leg stiffness in unknown conditions (Devita and Skelly, 1992). One of the reasons for increased leg stiffness is the non-predictability of the surrounding environment. In non-predictive operating environments, joint movements of the lower limbs during landing, particularly knee joint flexion movements, are reduced (Gambelli and Schepens, 2020). In addition, increased concentration on one's body movements increases leg stiffness and enhances body stability (Almonroeder et al., 2020). In the unknown condition, it is not possible to check the landing point, and the participants' awareness is likely to be directed toward their body movements rather than the external environment. From the above, leg stiffness could have increased due to the increased awareness of one's body, and as a result, the GRF during landing increased in the unknown condition.

Next, the increase in vGRF may be attributed to a decrease in negative work in the ankle joint and its shock-absorbing function. Shock absorption by the ankle joint immediately after landing is as important as that by the knee joint (Devita and Skelly, 1992). Therefore, the vGRF increases due to a decrease in the ankle joint shock absorption capability. Poor shock absorption is influenced by a decrease in ankle joint work after landing. In the present study, the plantar flexion angle upon landing was reduced in the unknown condition compared to that in the other two conditions, and the dorsiflexion motion that occurred after landing was also reduced. In contrast, no significant difference was observed in the internal plantar flexion moment after landing. In other words, although the power output of the ankle plantar flexors was the same, the dorsiflexion motion decreased, resulting in a decrease in workload at the ankle joint. In previous studies, the ankle joint plantar flexion angle at the time of landing was decreased to reduce the time until whole-foot contact and quickly find a supportive surface for landing movements in unstable environments (Gambelli and Schepens, 2020). In the present study, it was considered that the ankle joint plantar flexion angle at initial contact was reduced to ensure post-landing stability under the unknown condition. This may have resulted in decreased ankle dorsiflexion after landing, thus reducing shock-absorbing function at the ankle joint. Ankle plantar flexion angle decreases to balance the increased trunk extension during landing and the associated backward displacement of the CoM (Davis et al., 2019; Shimokochi et al., 2013). In the present study, trunk flexion after landing and the forward movement of the CoM were decreased. Therefore, the ankle dorsiflexion was considered to have decreased because of the decreased forward movement of the CoM. Thus, the shock-absorbing function at the ankle joint after landing was likely reduced to ensure that a supportive surface was quickly located or trunk stability was quickly achieved in the unknown condition.

The participants landed with their knees in a more flexed position, and the knee flexion excursion was reduced during landing in the unknown condition. In actual ACL injury situations, knee joint flexion changes up to 40 ms after landing have been reported to be as small as 23° or less (Koga et al., 2010), similar to the values in the unknown condition of this study. Moreover, knee joint stiffness was significantly higher in the unknown condition. The risk of ACL injury increases when the knee joint is subjected to a large GRF with high stiffness (Leppänen et al., 2017). Regarding knee joint motion, the risk of ACL injury is high when individuals land in an environment with limited visual input under conditions without prior knowledge of the height of fall.

Another factor that increases the risk of ACL injury is an increased pGRF (Sell et al., 2007). pGRF increases the anterior tibial shear force, which increases the load on the ACL. In the present study, the peak pGRF increased even with visual limitations alone, and increased more significantly with the loss of prior knowledge of the height of fall. Therefore, limited visual input increases the risk of ACL injury, and this risk is further increased by a lack of prior knowledge of the height of fall. The increased pGRF is caused by decreased trunk flexion. Decreased trunk flexion during landing suppresses forward CoM shift and increases the pGRF (Ali et al., 2014). In the present study, trunk flexion and forward shift of the CoM were also reduced owing to visual input limitations. This change was further magnified in the unknown condition. Therefore, the decreased trunk flexion during landing was considered to increase the pGRF in the unknown and known conditions. One of the reasons for the reduced trunk flexion is the prevention of falls. When falling and landing forward, the CoM tends to shift forward, increasing the risk of falling forward. In this case, decreasing the trunk flexion can suppress the forward shift of the CoM and prevent falls. Furthermore, during an unexpected stumble, the body responds by decreasing trunk movements to prevent a fall (Van Der Burg et al., 2005). Moreover, trunk flexion was found to decrease during landing in fear-inducing environments such as at high altitudes (Kim et al., 2013; Shaw et al., 2012; Zaback et al., 2019). In the present study, it was difficult to accurately predict the time and degree of impact during landing with limited visual input. In the unknown condition, prediction of the effects is even more challenging. Therefore, the subjects were more likely to lose their posture in the unknown and known conditions than in the control condition. From the above, it can be concluded that decreased trunk flexion and a corresponding increase in pGRF occurred as a countermeasure to prevent forward falls under the unknown and known conditions.

The present study has some limitations. First, since practice before the experiment is essential in terms of injury prevention, there is a limit to the subject's degree of complete inexperience in the experimental environment. Second, the participants' exercise history was not considered. Previous exercise experience can compensate for a lack of prior knowledge of the exercise environment (Kipp et al., 2013; McKinley and Pedotti, 1992; Mulligan et al., 2016). Therefore, a difference in motor control may exist under prior knowledge limitations depending on the subject's exercise experience. Third, participants were evaluated while they were completely deprived of visual information to unify the experimental environment. However, in actual sports activities, individuals infrequently perform movements with a complete lack of visual input. Therefore, there is room for improvement in method for blocking visual information (e.g., by narrowing the field of vision) to examine the risk of ACL injury during movement in more realistic situations.

5. Conclusions

The results of this study confirm that with limited prior knowledge of the fall height, the GRF increases not only in the vertical direction but also in the posterior direction when individuals have limited visual information while landing. It was suggested that decreased movement of the trunk and lower limb joints to prevent a forward fall was a factor in the increased risk of ACL injury. The changes in GRF and trunk and lower limb joint motion were relatively small when knowledge of the fall height was available. These results suggest that an accurate perception of falling height may help prevent ACL injuries. Therefore, future studies should examine whether cognitive function training, such as visual information processing training, can reduce the risk of ACL injuries during landing.

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